Research Article

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Residual efficacy of pyriproxyfen and hydroprene applied to wood, metal and concrete for control of stored-product insects

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Abstract

BACKGROUND: Pyriproxyfen and hydroprene are insect growth regulators (IGRs) that have been evaluated to control insect pests of field crops, but there are limited reports of efficacy against stored-product insects. A laboratory study was conducted to determine residual efficacy of pyriproxyfen and hydroprene on wood, metal and concrete surfaces. Pyriproxyfen was applied to the surfaces at 1.15 and 2.3 mg active ingredient [AI] m^{-2}, while hydroprene was applied at the label rate of 19 mg AI m^{-2}. Late-instar larvae of *Tribolium confusum* Jacqueline DuVal, *T. castaneum* (Herbst), *Oryzaephilus surinamenis* L., *Lasioderma serricorne* (F.) and *Plodia interpunctella* (Hübner) were exposed with a food source on the treated surfaces. Residual testing was conducted at 1, 28 and 56 days post-treatment.

RESULTS: Hydroprene was least persistent on concrete and generally most persistent on metal. Pyriproxyfen gave greater residual persistence than hydroprene, and there was no consistent difference in efficacy among the three surfaces. Efficacy varied among the five insect species, but generally *P. interpunctella* was the most tolerant species to both IGRs.

CONCLUSIONS: Pyriproxyfen gave effective residual control of primary stored-product insect species by inhibiting adult emergence of exposed larvae. Results show that pyriproxyfen can be a useful addition for pest management programs in mills, warehouses and food storage facilities.
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Keywords: pyriproxyfen; hydroprene; IGR; control; treated surfaces; stored-product insects; efficacy

1 INTRODUCTION

Although historical emphasis has been placed on stored-product insects as economic pests of bulk grains, they can also be prevalent in mills, processing plants and facilities where finished products are stored. Pest management in these diverse habitats is often accomplished through the use of insecticides; however, there is a recent emphasis on using integrated control methods, which can often include treatment with insecticides when control is necessary.[1,2] Targeted or directed control to certain areas is often emphasized, as is using reduced-risk insecticides to replace conventional neurotoxins.[2]

Insect growth regulators (IGRs) are an example of reduced-risk insecticides because they mimic hormones involved in the molting and developmental processes of immature insects. They have been extensively evaluated as grain protectants,[3,4] but more recently they are being examined for residual application as contact insecticides applied to flooring surfaces. A variety of different surfaces can exist in processing plants and food storage facilities, but three common surfaces are concrete, wood and metal, with many variations and differences within these broad categories. Insecticides are generally more persistent on metal, which is a non-porous surface, than on wood or concrete.[5–7] Efficacy of insecticides on wood and concrete is often quite variable, with differing order of persistence between the two, depending on the specific insecticide or the target insect species.[8]

In the United States of America (USA), the IGRs hydroprene, methoprene and, more recently, pyriproxyfen are labeled for use as contact insecticides on flooring surfaces. Laboratory studies have been conducted with late-instar larvae of *Plodia interpunctella* (Hübner), the Indianmeal moth,[9] *Tribolium castaneum* (Herbst) and *Tribolium confusum* Jacqueline DuVal[10–12] exposed on concrete treated with hydroprene at the label rate of 19 g active ingredient [AI] m^{-2}. These show that adult emergence can be suppressed depending on the exposure interval, but hydroprene can be volatile, and this lack of residual persistence compromises efficacy.[12]

During the past several years there have been a number of published studies documenting that pyriproxyfen will limit population growth of a variety of pest species from different agricultural systems, including, but not limited to, homopteran field crop pests,[13–18] mosquitoes,[19] ants[20,21] and cockroaches.[22] Pyriproxyfen shows evidence of lethal effects on immature life stages,

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sublethal effects such as morphological deformities in adults that were exposed as larvae to the IGR and residual persistence. However, there are limited data regarding susceptibility of stored-product insects. Arabi *et al.*[23] examined physiological effects in *Tenebrio molitor* L., the lesser mealworm, exposed to pyriproxyfen, but did not evaluate control. In addition, while this insect can be found in stored products, it is not generally considered an important pest species. Residual efficacy, impact of surface substrate and differential susceptibility among major stored-product insect pest species have not been evaluated for pyriproxyfen. Therefore, the objectives of this study were to determine: (1) residual persistence of pyriproxyfen; (2) efficacy on concrete, wood and metal; (3) susceptibility of a representative range of stored-product insect species. Tests were also done using the label rate of the IGR hydroprene as a comparison with pyriproxyfen.

2 MATERIALS AND METHODS

Late instars of *T. castaneum*, *T. confusum*, *Lasioderma serricorne* (F.), the cigarette beetle (Coleoptera: Anobiidae), *Oryzaephilus surinamensis* L., the sawtoothed grain beetle (Coleoptera: Cucujidae) and *P. interpunctella* were selected as the target species and life stage. The individual species represent common pests in food-processing facilities and are taxonomically diverse, while late-stage larvae are a challenging larval stage regarding susceptibility to exposure on a surface substrate. In addition, the authors wanted to use the late-stage larvae because of possible variation in earlier instars, and also to reduce their inherent mortality risks in handling. Stock cultures of individual species had been maintained in a laboratory at Oklahoma State University, Stillwater, OK, for approximately 20 years, and the original collection points were unknown. They were periodically supplemented with wild-caught individuals in facilities in the area, and all species were maintained on individual diets at standard rearing conditions of 27 °C and 60% relative humidity.

The experimental arenas were standard 100 × 15 mm disposable plastic petri dishes, which had an actual treated surface area of about 81 cm^2. Three different surfaces, wood, metal and concrete, were prepared in the experimental arenas as follows. The wood surface was a circular piece of 3.1 mm thick plywood painted with white latex wall paint, which fitted snugly inside the lid. A metal surface was constructed using the brass-coated metal flat insert from a canning jar lid, which also fitted inside the lid. For both of these surfaces, the sides were caulked to minimize larval escape under the treated surface. The concrete surface was constructed using a driveway patching material (Rockite®) mixed with water to create a slurry, and pouring the liquid into the petri dish bottom to create a smooth slab measuring about 3.1 mm in thickness. All of the experimental arenas were prepared several days prior to application of the insecticides. There were four insecticidal treatments, three surfaces, three residual testing periods, five insect species and four replicates, which was a total of 720 experimental arenas that were prepared for the experiment, along with an equal number of ventilated lids to minimize escape from the arenas.

The insecticide treatments were as follows. For each replicate, each of the 45 control arenas was sprayed with 1.95 µL of distilled water, using a Badger 100 artist's airbrush (Badger Corporation, Franklin Park, IL). Solutions of pyriproxyfen were prepared in distilled water using a commercial 13 g AI L^{-1} EC (Archer®) to give an application rate of either 1.15 or 2.3 mg AI m^{-2} on the treated surface, using a spray volume of 1.95 µL. A solution was prepared for each of the four replicates, and each concentration of pyriproxyfen was sprayed onto the respective surface using the artists' airbrush described above. In addition, the undersurface of the ventilated lid was also sprayed at the same rate to ensure that any larvae that crawled off the treated surface onto the undersurface of the lid would be exposed to the insecticide. Solutions of hydroprene were prepared using a commercial 90 g AI L^{-1} EC (Gentrol®) to give an application rate of 19 mg AI m^{-2}, which is the label rate. The volume rate of 1.95 µL per 81 cm^2 was used in the test because it is proportional to the label rate for application as a surface treatment. The undersurfaces of the covering lids used for this treatment were sprayed as described for the two rates of pyriproxyfen. All surfaces for a given replicate were sprayed on the same day, and held on an open laboratory counter until they were used for the insect exposures following evaporation of the water.

Test life stages of each insect species were applied at 1, 28 and 56 days post-treatment by placing 20 larvae of a particular species on its own individual test arena of a particular surface and replicate. Approximately 700 mg of whole-wheat flour was placed on each arena, and the ventilated lids were then affixed to the arenas using hot glue and tape to attach the lids so as to minimize escape of larvae that climbed the walls of the arena. All test insects were exposed on the surfaces for 28 days, then transferred to a clean, ventilated petri dish with 700 mg of flour for 28 days, after which time the number of insects that had emerged as normal healthy adults, alive and without morphological defects that are a common manifestation from exposure to insect growth regulators in the immature stage, were counted. Separate trials were conducted at the 1, 28 and 56 days post-exposure periods, as described above. All treatments were conducted in the laboratory, and all arenas were held in this laboratory as well. Environmental conditions were not monitored, but were typically about 23 °C and 40–60% relative humidity.

Control mortality of all species was variable on all of the treated surfaces, but no corrections were made because the control mortality appeared to be random, with no pattern of declining emergence in the treatments with lower emergence in the controls. Data were analyzed with species, exposure time, insecticidal treatment and surface as main effects, using the general linear models procedure (PROC GLM) of the Statistical Analysis System,[24] with the variable of interest adult emergence. Data were transformed by square root prior analysis to stabilize variances; however, data reported are the actual means. Treatment means were separated using the Waller–Duncan *k*-ratio *t*-test.[24]

3 RESULTS

The overall ANOVA shows that all main effects, and several associated interactions, were significant at $P < 0.05$ (Table 1). Data were then analyzed to determine effects of residual exposure time, treatment and surface for each individual species. The ANOVA for *T. confusum* shows that main effects treatment and surface were significant ($F = 258.8$, df = 3, 107, $P < 0.01$; $F = 3.1$, df = 2, 107, $P = 0.04$), but not residual exposure time ($F = 2.7$, df = 2, 107, $P = 0.07$). Only the time × treatment interaction was significant ($P < 0.01$). Adult emergence in untreated controls was above 90%, except on metal at 56 days post-treatment. In both pyriproxyfen treatments, emergence of the exposed larvae did not exceed 4.2%, in contrast to emergence of 0–58.7% in larvae exposed on surfaces treated with hydroprene (Table 2). At 28 and 56 days, emergence was lower for larvae exposed on metal and concrete treated with either rate of pyriproxyfen compared with emergence on those surfaces treated with hydroprene. There were no differences in emergence with respect to surface at the 1 and 28 day trials, but

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Table 1. ANOVA for main effects species, residual exposure time, treatment and surface

Source	df	*F*	*P*
Time	2	19.9	<0.01
Treatment	3	673.4	<0.01
Species	4	33.3	<0.01
Surface	2	3.3	0.038
Time × treatment	6	20.8	<0.01
Time × species	8	3.5	<0.01
Time × surface	4	0.7	0.579
Treatment × species	12	10.1	<0.01
Treatment × surface	6	6.1	<0.01
Species × surface	8	2.0	0.050
Time × treatment × species	24	1.6	0.035
Time × treatment × surface	12	2.0	0.030
Treatment × species × surface	24	1.3	0.162
Time × treatment × species × surface	64	0.6	0.992
Error	538		

Table 2. Percentage emergence, mean (± SE), of normal, healthy-appearing adult *Tribolium confusum* from late instars exposed at 1, 28 and 56 days post-treatment on untreated wood, metal and concrete (UTC) and on these surfaces treated with 1.15 and 2.3 mg AI m^{-2} pyriproxyfen (P1 and P2) and 19 mg AI m^{-2} hydroprene (H)[a]

Time	Treatment	Wood	Metal	Concrete
1	UTC	97.2 (±1.6) aA	98.6 (±1.4) aA	95.0 (±5.0) aA
	P1	3.7 (±2.3) bA	0.0 (±0.0) bA	0.0 (±0.0) bA
	P2	0.0 (±0.0) bA	0.0 (±0.0) bA	0.0 (±0.0) bA
	H	0.0 (±0.0) bA	1.5 (±1.5) bA	0.0 (±0.0) bA
28	UTC	95.1 (±3.4) aA	98.3 (±1.2) aA	100.0 (±0.0) aA
	P1	0.0 (±0.0) bA	0.0 (±0.0) cA	0.0 (±0.0) cA
	P2	3.3 (±3.3) bA	0.0 (±0.0) cA	0.0 (±0.0) cA
	H	18.8 (±18.8) bA	27.9 (±16.3) bA	45.6 (±26.3) bA
56	UTC	91.8 (±5.3) aA	74.3 (±17.5) aA	98.7 (±0.3) aA
	P1	4.2 (±4.2) bA	0.0 (±0.0) cA	3.1 (±3.1) bA
	P2	0.0 (±0.0) bA	0.0 (±0.0) cA	0.0 (±0.0) bA
	H	8.5 (±5.6) bB	14.6 (±8.6) bB	58.7 (±23.8) aA

[a] Significant difference between treatments (columns) denoted by different lower-case letters, significant difference between surfaces (rows) denoted by different upper-case letters ($P < 0.05$, Waller–Duncan *k*-ratio *t*-test, SAS Institute, 2001).

at 56 days emergence in the hydroprene treatments was greater for larvae exposed on concrete than on wood and metal.

Main effects treatment, surface and residual exposure time were all significant for adult emergence of exposed *T. castaneum* at $P < 0.01$ ($F = 106.0$, df = 2, 107; $F = 4.9$, df = 2, 107; $F = 8.2$, df = 2, 107 respectively). The time × treatment and time × surface interactions were also significant at $P < 0.01$. Adult emergence in untreated controls ranged from 52.6 to 88.0% (Table 3), and again this variable mortality in the controls did not appear to affect significance among the insecticide treatments. There was no difference among the three insecticide treatments at 1 or 28 days, but at 56 days emergence was lower for larvae exposed on metal and concrete treated with either rate of pyriproxyfen compared with emergence from larvae exposed on these surfaces treated with hydroprene. Adult emergence was 0–18.8% for the exposures on surfaces treated with pyriproxyfen and 2.7–48.4% on surfaces treated with hydroprene. There were no differences in emergence with respect to surface, except for an abnormally low emergence in untreated controls exposed on metal at 28 days.

Table 3. Percentage emergence, mean (± SE), of normal adult *Tribolium castaneum* from late instars exposed at 1, 28 and 56 days post-treatment on untreated wood, metal and concrete (UTC) and on these surfaces treated with 1.15 and 2.3 mg AI m^{-2} pyriproxyfen (P1 and P2) and 19 mg AI m^{-2} hydroprene (H)[a]

Time	Treatment	Wood	Metal	Concrete
1	UTC	69.3 (±15.6) aA	60.4 (±19.4) aA	74.8 (±11.5) aA
	P1	0.0 (±0.0) bA	0.0 (±0.0) bA	0.0 (±0.0) bA
	P2	0.0 (±0.0) bA	0.0 (±0.0) bA	3.5 (±3.5) bA
	H	1.3 (±1.3) bA	0.0 (±0.0) bA	3.5 (±3.5) bA
28	UTC	57.4 (±12.3) aA	15.3 (±5.6) aB	59.5 (±16.3) aA
	P1	0.0 (±0.0) bA	0.0 (±0.0) bA	0.0 (±0.0) bA
	P2	0.0 (±0.0) bA	0.0 (±0.0) bA	0.0 (±0.0) bA
	H	0.0 (±0.0) bA	0.0 (±0.0) bA	0.0 (±0.0) bA
56	UTC	58.2 (±9.6) aA	44.9 (±13.4) aA	67.6 (±6.7) bA
	P1	0.0 (±0.0) cB	0.0 (±0.0) cB	12.5 (±7.5) bA
	P2	18.8 (±6.5) bA	2.5 (±2.5) cB	5.9 (±5.9) bB
	H	2.7 (±1.6) cB	28.3 (±7.4) bA	48.4 (±26.6) aA

[a] Significant difference between treatments (columns) denoted by different lower-case letters, significant difference between surfaces (rows) denoted by different upper-case letters ($P < 0.05$, Waller–Duncan *k*-ratio *t*-test, SAS Institute, 2001).

Main effects treatment and residual exposure time were significant for emergence of adult *L. serricorne* at $P < 0.01$ ($F = 74.6$, df = 2, 107; $F = 5.7$, df = 2, 107), but not surface ($F = 0.5$, df = 2, 107, $P = 0.61$). Only the time × treatment interaction was significant ($P < 0.01$). Adult emergence in untreated controls was variable and ranged from 55.2 to 88.0% (Table 4), but this variable mortality did not appear to affect significance among the insecticide treatments. There was no difference among the three insecticide treatments at 1 day, while at 28 and 56 days adult emergence was lower on the pyriproxyfen treatments than in the hydroprene treatment, except for wood at 28 days. Adult emergence was 27–75% on hydroprene at 28 and 56 days, and did not exceed 10.7% in the pyriproxyfen treatments.

Main effects treatment and residual exposure time were significant at $P < 0.01$ for emergence of adult *O. surinamensis* ($F = 118.3$, df = 2, 107; $F = 10.4$, df = 2, 107), but not surface ($F = 2.7$, df = 2, 107, $P = 0.07$). The time × treatment interaction was significant ($P < 0.01$), and, while the overall ANOVA indicated non-significance for surface, the treatment × surface interaction was also significant at $P < 0.01$. Adult emergence in untreated controls was at least 64.3% (Table 5), but, as with the other species, this variation in adult mortality in untreated controls did not affect significance in the treatments. With this species there was considerable variation in efficacy on wood, such that in several instances adult emergence was actually greater in the higher rate of pyriproxyfen compared with the lower rate. At 28 and 56 days adult emergence from larvae exposed on concrete and metal was always lower in the pyriproxyfen treatments than in the hydroprene treatment. At all three time periods, adult emergence from larvae exposed on the wood treated with pyriproxyfen was greater than emergence on the concrete surface.

Table 4. Percentage emergence, mean (± SE), of normal adult *Lasioderma serricorne* from late instars exposed at 1, 28 and 56 days post-treatment on untreated wood, metal and concrete (UTC) and on these surfaces treated with 1.15 and 2.3 mg AI m^{-2} pyriproxyfen (P1 and P2) and 19 mg AI m^{-2} hydroprene (H)[a]

Time	Treatment	Wood	Metal	Concrete
1	UTC	55.3 (±19.1) a	55.2 (±17.2) a	63.7 (±21.9) a
	P1	6.7 (±3.9) b	1.3 (±1.3) b	1.3 (±1.3) b
	P2	4.4 (±4.4) b	3.1 (±3.1) b	5.9 (±5.9) b
	H	1.3 (±1.3) b	7.5 (±7.7) b	3.7 (±3.7) b
28	UTC	69.8 (±12.3) a	88.0 (±7.5) a	71.0 (±16.0) a
	P1	10.7 (±4.9) b	0.0 (±0.0) b	4.2 (±4.2) c
	P2	2.9 (±2.9) b	1.2 (±1.2) b	2.9 (±1.2) c
	H	27.0 (±19.5) b	75.0 (±29.6) a	36.4 (±21.0) b
56	UTC	67.0 (±14.3) a	68.6 (±15.1) a	52.6 (±16.0) a
	P1	2.9 (±2.9) b	2.2 (±2.2) b	0.0 (±0.0) b
	P2	3.7 (±3.7) b	1.3 (±1.3) b	2.6 (±2.6) b
	H	36.5 (±16.1) a	43.6 (±10.6) a	54.2 (±5.6) a

[a] Significant difference between treatments (columns) denoted by different lower-case letters ($P < 0.05$, Waller–Duncan *k*-ratio *t*-test, SAS Institute, 2001). No analysis done for surfaces because the ANOVA indicated no significant differences ($P \geq 0.05$).

Table 5. Percentage emergence, mean (± SE), of normal adult *Oryzaephilus surinamenis* from late instars exposed at 1, 28 and 56 days post-treatment on untreated wood, metal and concrete (UTC) and on these surfaces treated with 1.15 and 2.3 mg AI m^{-2} pyriproxyfen (P1 and P2) and 19 mg AI m^{-2} hydroprene (H)[a]

Time	Treatment	Wood	Metal	Concrete
1	UTC	71.1 (±9.7) aA	77.5 (±11.0) aA	70.9 (±10.2) aA
	P1	24.9 (±6.1) bA	5.0 (±5.0) aB	12.1 (±3.1) aAB
	P2	9.8 (±5.6) cA	5.4 (±3.2) aA	2.5 (±1.4) bA
	H	9.1 (±5.9) cA	4.0 (±2.5) aA	0.0 (±0.0) bA
28	UTC	66.6 (±12.1) a	64.3 (±5.9) a	74.9 (±6.0) a
	P1	26.4 (±12.2) bA	3.3 (±2.0) bB	5.6 (±5.6) bB
	P2	38.8 (±8.7) bA	17.9 (±16.2) bAB	0.0 (±0.0) bB
	H	32.4 (±12.0) bB	45.7 (±10.0) aA	52.9 (±13.8) aAB
56	UTC	67.0 (±14.3) aA	80.1 (±8.6) aA	75.0 (±10.9) aA
	P1	14.0 (±4.5) bcA	1.8 (±1.8) bB	6.9 (±1.0) bB
	P2	30.1 (±11.3) bA	3.6 (±3.6) bB	2.6 (±2.6) cB
	H	56.1 (±10.1) abA	56.7 (±10.2) aA	71.7 (±9.4) aA

[a] Significant difference between treatments (columns) denoted by different lower-case letters, significant difference between surfaces (rows) denoted by different upper-case letters ($P < 0.05$, Waller–Duncan *k*-ratio *t*-test, SAS Institute, 2001).

Main effects treatment and residual exposure time were significant at $P < 0.01$ for emergence of adult *P. interpunctella* ($F = 188.3$, df = 2, 108; $F = 7.3$, df = 2, 108), but, as with *L. serricorne* and *O. surinamenis*, surface was not significant ($F = 0.97$, df = 2, 108, $P = 0.417$). The time × treatment interaction was significant ($P < 0.01$), and, even though the overall ANOVA indicated non-significance for surface, the treatment × surface interaction was also significant at $P < 0.01$. No other interactions were significant ($P \geq 0.05$). Adult emergence in untreated controls always exceeded 90% (Table 6), which was generally much higher than the adult emergence from exposed beetle larvae. With *P. interpunctella* there was also considerable variation in efficacy on wood such that there was generally no difference in emergence between either rate of pyriproxyfen and hydroprene. However, at 28 and 56 days adult emergence from larvae exposed on concrete and metal was always lower in the pyriproxyfen treatments than in the hydroprene treatment. At all three time periods, adult emergence varied on the three surfaces, with seemingly little consistency.

A final analysis was done to determine order of species susceptibility at each time period by examining the combined dataset and analyzing the data for differences among species at each residual time period for the three IGR treatments (controls were excluded) on each of the three surfaces. When there were significant differences with respect to species, the least susceptible species, based on emergence of normal healthy adults from exposed larvae, was usually either *P. interpunctella* or *O. surinamensis*, while the most susceptible species was usually either *T. confusum* or *T. castaneum*. At 1 day, the order of species susceptibility was significant only for the high rate of pyriproxyfen on wood and concrete (Table 7). At 28 days there were significant differences in species susceptibility for the low rate of pyriproxyfen on wood and concrete, the high rate of pyriproxyfen on wood and hydroprene on metal and concrete (Table 8). At 56 days there were significant differences for both rates of pyriproxyfen on wood only, and hydroprene on wood and metal (Table 9).

Table 6. Percentage emergence, mean (± SE), of normal adult *Plodia interpunctella* from late instars exposed at 1, 28 and 56 days post-treatment on untreated wood, metal and concrete (UTC) and on these surfaces treated with 1.15 and 2.3 mg AI m^{-2} pyriproxyfen (P1 and P2) and 19 mg AI m^{-2} hydroprene (H)[a]

Time	Treatment	Wood	Metal	Concrete
1	UTC	93.7 (±4.7) aA	94.7 (±2.1) aA	98.7 (±1.2) aA
	P1	16.7 (±10.0) bA	16.2 (±9.9) bA	20.0 (±13.4) bA
	P2	15.0 (±11.9) bA	11.3 (±9.7) bA	23.1 (±15.7) bA
	H	4.4 (±4.4) bA	2.5 (±2.5) bA	0.0 (±0.0) cA
28	UTC	96.2 (±2.4) aA	97.4 (±1.6) aA	97.4 (±2.6) aA
	P1	35.0 (±16.4) bA	7.9 (±7.9) cA	23.9 (±16.1) bA
	P2	24.4 (±10.8) bcA	5.0 (±3.5) cA	16.4 (±14.5) bA
	H	9.5 (±3.2) cB	32.6 (±9.7) bA	31.9 (±3.8) bA
56	UTC	100 (±0.0) aA	100 (±0.0) aA	100 (±0.0) aA
	P1	34.0 (±6.7) bA	7.5 (±6.0) bB	18.7 (±12.9) bA
	P2	25.3 (±4.1) bA	2.6 (±2.6) bB	10.4 (±5.4) bAB
	H	33.6 (±6.7) bA	63.7 (±14.4) aA	56.2 (±13.2) aA

[a] Significant difference between treatments (columns) denoted by different lower-case letters, significant difference between surfaces (rows) denoted by different upper-case letters ($P < 0.05$, Waller–Duncan *k*-ratio *t*-test, SAS Institute, 2001).

4 DISCUSSION

In previous studies involving the commercial hydroprene formulation Gentrol® applied on the same type of concrete as used in this study, at an application rate of 19 mg AI m^{-2}, *Tribolium castaneum* was more susceptible than *T. confusum*.[10,12] Tests with a volatile formulation of hydroprene and with experimental formulations of liquid hydroprene applied at the same concentration of 19 mg AI m^{-2} produced the same result of greater susceptibility of *T. castaneum* than *T. confusum*,[11,12] as did the present test with different strains of the same species. Other tests with the same

Table 7. Order of species susceptibility, from least susceptible to most susceptible, of the five species exposed on the surfaces treated with 1.15 mg AI m^{-2} pyriproxyfen (P1), at 1 day post-treatment[a]

Treatment	Wood	Metal	Concrete
P1	a *P. interpunctella*	NS	a *P. interpunctella*
	ab *O. surinamenis*	NS	a *O. surinamenis*
	bc *L. serricorne*	NS	b *L. serricorne*
	c *T. confusum*	NS	b *T. confusum*
	c *T. castaneum*	NS	b *T. castaneum*

[a] Species listed in order of least to most susceptible, based on adult emergence reported in Tables 2 to 5. Species preceded by different letters denotes that adult emergence was significantly different ($P < 0.05$, Waller–Duncan *k*-ratio *t*-test, SAS Institute). NS denotes no significance ($P \geq 0.05$). No significant differences ($P \geq 0.05$) for treatments P2 and H.

Table 8. Order of species susceptibility, from least susceptible to most susceptible, of the five species exposed on the surfaces treated with 1.15 and 2.3 mg AI m^{-2} pyriproxyfen (P1 and P2) and 19 mg AI m^{-2} hydroprene (H), at 28 days post-treatment[a]

Treatment	Wood	Metal	Concrete
P1	a *P. interpunctella*	NS	a *P. interpunctella*
	ab *O. surinamenis*	NS	ab *O. surinamenis*
	b *L. serricorne*	NS	bc *L. serricorne*
	c *T. confusum*	NS	c *T. confusum*
	c *T. castaneum*	NS	c *T. castaneum*
P2	a *P. interpunctella*	NS	NS
	ab *O. surinamenis*	NS	NS
	b *L. serricorne*	NS	NS
	c *T. confusum*	NS	NS
	c *T. castaneum*	NS	NS
H	NS	a *L. serricorne*	a *O. surinamenis*
	NS	ab *P. interpunctella*	ab *P. interpunctella*
	NS	ab *O. surinamenis*	ab *L. serricorne*
	NS	bc *T. confusum*	ab *T. confusum*
	NS	c *T. castaneum*	b *T. castaneum*

[a] Species listed in order of least to most susceptible, based on adult emergence reported in Tables 2 to 6. Species preceded by different letters denotes that adult emergence was significantly different ($P < 0.05$, Waller–Duncan *k*-ratio *t*-test, SAS Institute). NS denotes no significance ($P \geq 0.05$).

strains involving contact insecticides have also shown differences in susceptibility between these two beetle species, but the order of susceptibility often varies. *Tribolium confusum* was more susceptible than *T. castaneum* to the pyrethroid cyfluthrin[25] and the pyrrole chlorfenapyr,[8] while the reverse was true for inert dusts.[26] This difference in insecticide susceptibility between *T. confusum* and *T. castaneum* could be dependent on individual insecticides and their modes or action, differences in how the two species absorb a particular insecticide or behavioral characteristics that affect exposure to that insecticide. Nevertheless, these differing results in species susceptibility between these two closely related beetle species emphasize the importance of identifying the specific species that is being targeted for control in a storage facility, and adjusting the management plan according to the insecticides that are registered for control.

Table 9. Order of species susceptibility, from least susceptible to most susceptible, of the five species exposed on the surfaces treated with 1.15 and 2.3 mg AI m^{-2} pyriproxyfen (P1 and P2) and 19 mg AI m^{-2} hydroprene (H), at 56 days post-treatment[a]

Treatment	Wood	Metal	Concrete
P1	a *P. interpunctella*	NS	NS
	b *O. surinamenis*	NS	NS
	c *L. serricorne*	NS	NS
	c *T. confusum*	NS	NS
	c *T. castaneum*	NS	NS
P2	a *P. interpunctella*	NS	NS
	a *O. surinamenis*	NS	NS
	a *L. serricorne*	NS	NS
	b *T. confusum*	NS	NS
	b *T. castaneum*	NS	NS
H	a *P. interpunctella*	a *P. interpunctella*	NS
	a *O. surinamenis*	a *O. surinamenis*	NS
	ab *L. serricorne*	a *L. serricorne*	NS
	bc *T. confusum*	b *T. confusum*	NS
	c *T. castaneum*	ab *T. castaneum*	NS

[a] Species listed in order of least to most susceptible, based on adult emergence reported in Tables 2 to 5. Species preceded by different letters denotes that adult emergence was significantly different ($P < 0.05$, Waller–Duncan *k*-ratio *t*-test, SAS Institute). NS denotes no significance ($P \geq 0.05$).

It was apparent that hydroprene had lost effectiveness at 28 days post-treatment, and showed less residual efficacy on concrete than on the metal surface. This is not surprising, as many tests with insecticides and treated surfaces have shown a loss in either potency or efficacy when adult stored-product insects are exposed on porous surfaces such as concrete compared with metal or even wood surfaces.[5,7,27,28] However, it must be emphasized that there can be differences among materials labeled as concrete, wood and metal. For example, Toews *et al*.[6] conducted tests in which *T. castaneum* and *T. confusum* were exposed on four different surfaces, including concrete, treated with the biological insecticide spinosad. They recorded greater efficacy on concrete, which was formulated from a dry concrete mix, than on galvanized steel. One possible reason for this difference was that the concrete surface used in their study produced a dry and dusty surface, which could have caused cuticle abrasion, thereby enhancing penetration of spinosad into the body of an individual adult beetle. Therefore, when reporting the results from a study involving treated surfaces, it is important to give a detailed description of how the surfaces were prepared, to facilitate comparison with results obtained by other researchers. In addition, in contrast to most previously published studies, which involved tests in which contact insecticides were applied on the surfaces to control adult beetles, the present tests were conducted with late-stage larvae.

The results of the present study were also analyzed for differences in susceptibility among the five insect species that were tested. In the test there were three surfaces, three testing times and three insecticide rates, or 27 possible comparisons. In 11 of the 27 comparisons there were significant differences in the emergence of normal healthy adults among all the species. In every case where significant differences occurred, larvae of *P. interpunctella* were less susceptible than larvae of either

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T. castaneum or *T. confusum*, i.e. emergence of normal healthy adults from exposed larvae was greater in *P. interpunctella* than in the two beetle species. In tests involving exposure of late-stage *P. interpunctella* on grains or peanuts, the amount of insecticide needed to kill late-stage larvae is often 5–20 or more times greater than that needed to kill adult *T. castaneum* and other stored-grain beetles.[29–32] While such a large discrepancy was not noted in the present test, it was apparent that *P. interpunctella* was the least susceptible species to both pyriproxyfen and hydroprene.

Pyriproxyfen had not been evaluated for control of stored-product insects, but tests have been conducted on insect pests in other agricultural systems. Tests have also been conducted in which susceptibility of some beneficial insect species to pyriproxyfen has been assessed along with the susceptibility of the pest species. A field study in cotton by Naranjo and Akey[33] showed that the insecticide acetamiprid generally resulted in lower pest densities of *Bemisia tabaci* (Gennadius), the sweet potato whitefly, compared with applications of the IGRs pyriproxyfen and buprofezin; however, the IGRs had less overall effect on the predator communities associated with *B. tabaci* compared with acetamiprid. Liu and Stansley[34] did show sublethal effects when adult *Delphastus catalinae* (Horn), a predator of *B. tabaci*, fed on eggs of *B. tabaci* treated with buprofezin or pyriproxyfen, but pyriproxyfen generally only caused a reduction in fecundity of female *D. catalinae*. This effect was reversed when the treated eggs were replaced with untreated eggs. Pyriproxyfen applied at label rates did not affect adult *Cryptolaemus montrouzieri* Mulsant, the mealybug destroyer, or the parasitoid *Leptomastix dactylopii* How., both of which are important natural enemies of citrus mealybug, *Planococcus citri* (Rissi).[35] Applications at 4 times the label rate did not affect the parasitization rate or the percentage of adult emergence. Finally, there were no lethal or sublethal effects on adult *Coccinella septempunctata* L., the seven-spot ladybird beetle, exposed to pyriproxyfen.[36] However, all of the tests cited above were done with beneficial insects in field crop systems. There are no published journal studies describing effects of pyriproxyfen on predators or parasites of stored-product insects.

In conclusion, pyriproxyfen generally showed a much greater residual persistence than hydroprene on the wood, metal and concrete surfaces used in this study. The low application rate of pyriproxyfen, combined with the residual persistence, indicates that pyriproxyfen could be used in management programs for flour mills, processing plants and food warehouses to control stored-product insects.

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